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The program supported the development of high bandwidth heterojunction bipolar transistors (HBTs) for use in ultra-high frequency radar and communication systems. This three-year program led to improvement in state-of-the-art HBT bandwidth and to the development of design methodologies for transistor circuits at millimeter-wave (mm-wave) frequencies. Under funding from this program, the first small-signal HBT amplifiers in the 140-220GHz frequency band were demonstrated.

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Final Technical Report, AFOSR Program.
"80-240 GHz Radar and Communications in Transferred Substrate HBT Technology"
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Abstract

The program supported the development of high bandwidth heterojunction bipolar transistors (HBTs) for use in ultra-high frequency radar and communication systems. This three-year program led to improvement in state-of-the-art HBT bandwidth, and to the development of design methodologies for transistor circuits at millimeter-wave (mm-wave) frequencies. Under funding from this program, the first small-signal HBT amplifiers in the 140-220 GHz frequency band were demonstrated.

Objectives

The program objective was to demonstrate basic circuits for mm-wave radar and communication systems utilizing InP-based transferred-substrate heterojunction bipolar transistors (HBTs). The transferred-substrate HBT process, developed under joint AFOSR and ONR support, has demonstrated record values of extrapolated transistor power-gain cutoff frequency f_{max}. The high available gain at mm-wave frequencies from state-of-the-art HBTs will enable the realization of radar and communication systems over the full 30-300 GHz millimeter-wave frequency range. Under this program, issues relating to the development of transistor-based integrated circuits for these ultra-high frequency systems have been addressed. These issues include: device scaling for increased bandwidth and margin in circuit designs, measurement and modeling of highly-scaled transistors across the entire mm-wave frequency band, and circuit design techniques at ultra-high frequencies.

Approach

Device scaling, the reduction of lithographic feature sizes and epitaxial layer thicknesses, is essential to improving transistor bandwidth. The transferred-substrate process developed at UCSB has allowed for aggressive scaling of the III-V HBT. In a traditional, III-V mesa-HBT a large parasitic base-collector capacitance lies underneath the base Ohmic contacts. Narrowing the base Ohmic contact to reduce this capacitance will result in an increase in base contact resistance, thus frustrating efforts to increase f_{max}. The substrate-transfer technique (outlined in Figure 1) provides access to both sides of the device epitaxy, and therefore, allows the simultaneous realization of highly scaled base-emitter and base-collector junctions, without a subsequent increase in base resistance. By scaling both transistor junctions to submicron dimensions, record values of transistor power gain have been obtained. An additional benefit of the transferred-substrate process is that it provides a low loss microstrip transmission line wiring environment with a very predictable characteristic impedance. The thin dielectric (5μm) wiring environment reduces line-to-line coupling and will not support higher-order propagation modes over the design frequencies of interest. These features are of great benefit in mm-wave tuned-circuit designs.

The transferred-substrate technology provides a promising vehicle for the development of radar and communication systems at frequencies up to 220 GHz. The basic circuits that form the core of these systems (amplifiers, oscillators, mixers) are of low enough complexity that they can be demonstrated in a university-based integrated circuit process. Currently, electronics at frequencies over 100 GHz are limited in function due to the reliance on Gunn and IMPATT oscillator diodes and Schottky diode frequency multipliers. The demonstration of transistor-based electronics at these frequencies will allow for the development of more fully functional system architectures.

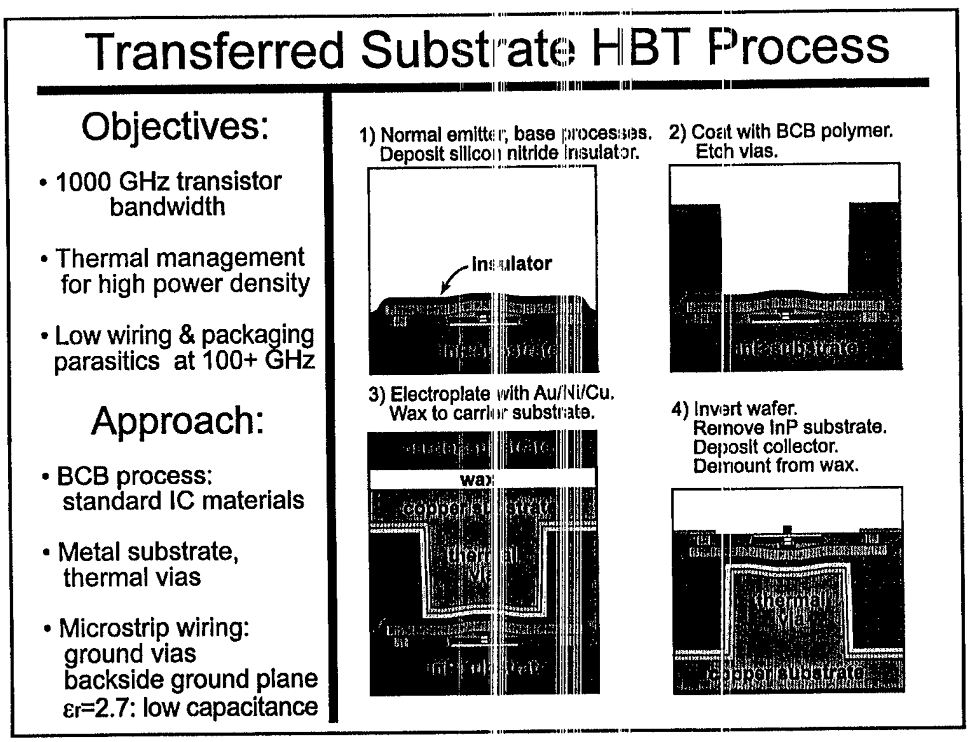


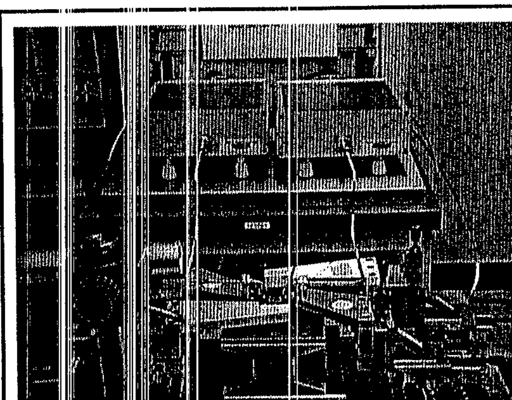
Figure 1: Transferred-substrate process flow

Accomplishments

Previous generations of transferred-substrate HBTs had demonstrated record-high power gains in the W-band (75-110 GHz) frequency range. A 140-220 GHz vector network analyzer, obtained by UCSB through a DURIP proposal, provided the means to measure transistors and circuits at even higher frequencies. The measurement set-up (Figure 2) consists of an Agilent HP8510 network analyzer with Oleson Microwave Lab mm-wave extenders. GGB on-wafer probes are interfaced to the extenders through short lengths of WR-5 waveguide. The test set-up has provided a repeatable on-wafer measurement system for full two-port S-parameter measurements of transistors and circuits. The characterization of submicron HBTs is particularly challenging, and a great deal of effort has been extended to develop an accurate on-wafer measurement methodology across the mm-wave band.

140-220 GHz VNA Measurements

- HP8510C VNA with *Oleson Microwave Lab* mmwave Extenders
- *GGB Industries* coplanar wafer probes with WR-5 waveguide connectors
- Full-two port T/R measurement capability
- Line-Reflect-Line calibration with on-wafer standards
- Internal bias Tee's in probes for biasing active devices



UCSB 140-220 GHz VNA Measurement Set-up

Figure 2: 140-220 GHz vector network analyzer measurement set-up.

Accurately characterizing transistors is important for developing circuit models for computer-aided design simulations, and for predicting the maximum usable frequency of a device. Recent measurements of transferred-substrate HBTs have demonstrated a small-negative output conductance over parts of the mm-wave band. Standard circuit models do not predict such behavior, and the negative output conductance is believed to arise from second-order transport effects in the collector space charge region. These effects would not be evident in a traditional mesa-HBT device as the large collector-base junction capacitance dominates the output conductance. A consequence of the observed negative output conductance, is an unbounded measure of the transistor's unilateral power gain, and an inability to predict the transistor's f_{max}. However, transistor power gains (Figure 3) show a high available power gain to the limits of commercially available measurement systems.

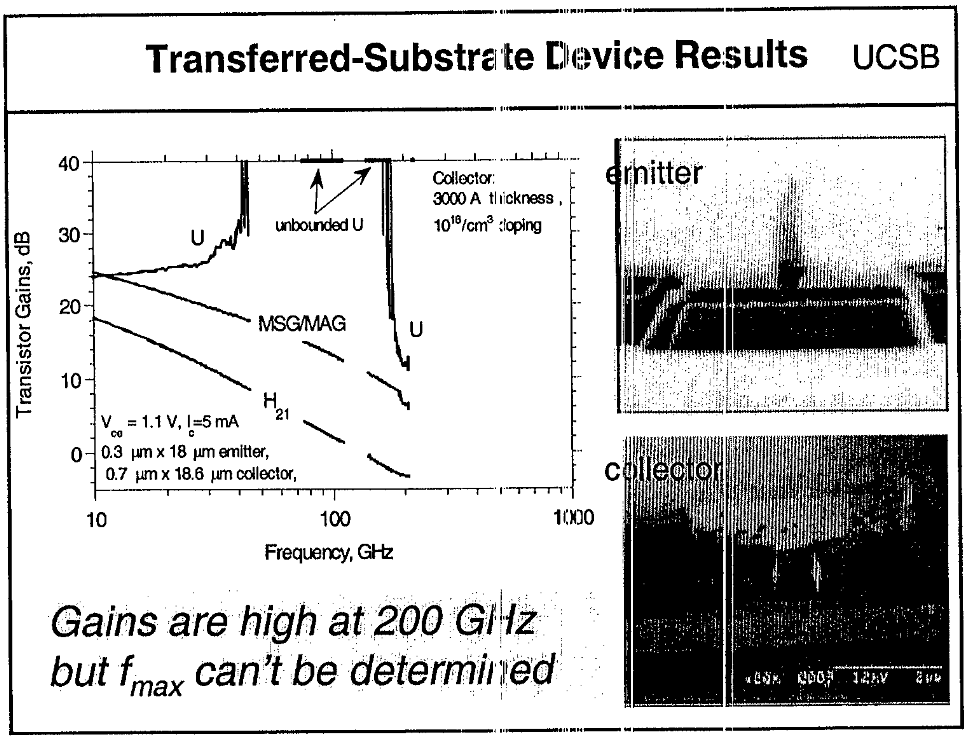


Figure 3: Measured transistor power gains of submicron HBT.

The transferred-substrate process was used to fabricate a single-stage tuned amplifier at 174 GHz (Figure 4). The amplifier was found to have a peak gain of 6.3 dB at 175 GHz, with a gain of better than 3 dB from 140 to 190 GHz. Both the input and output return loss were better than 10 dB at 175 GHz. This result represents the first HBT amplifier demonstrated in the 140-220 GHz band, and the gain-per-stage of the amplifier was amongst the highest reported from any transistor technology. Based on this work, oscillators and multi-stage amplifiers in the 140-220 GHz band were being designed.

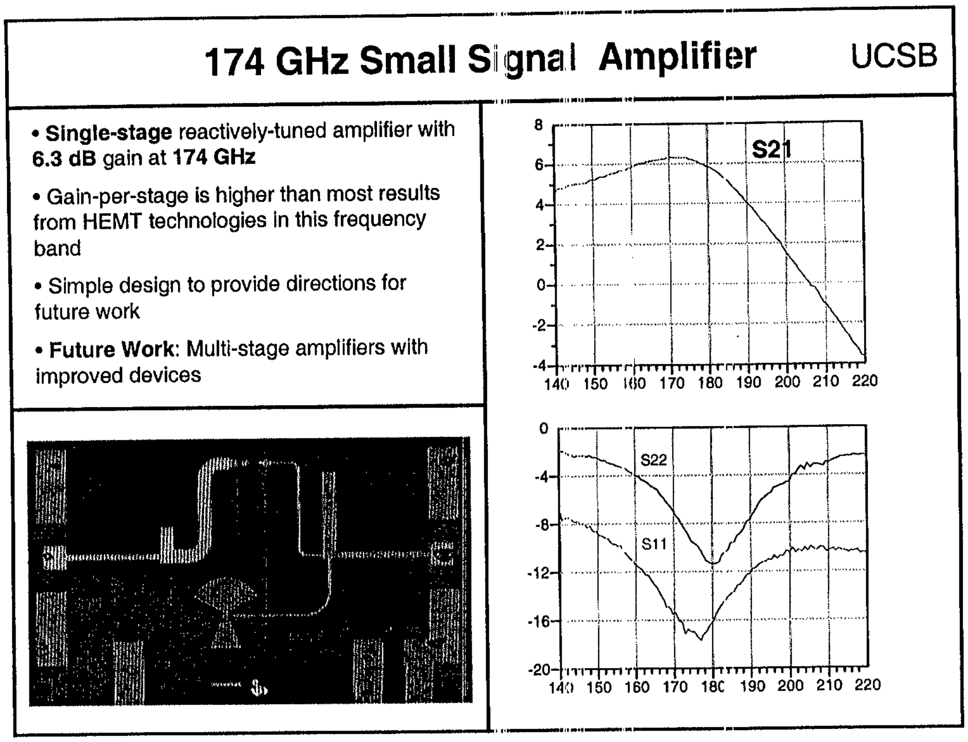


Figure 4: Single-stage tuned amplfier in transferred-substrate technology

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Publications for work supported under the contract

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3	2001	M. Urteaga, D. Scott, T. Mathew, S. Krishnan, Y. Wei and M.J.W. Rodwell, "185 GHz Monolithic Amplifier in InGaAs/InA1As Transferred-Substrate HBT Technology."	*IEEE MTT-S 2001 International Microwave Symposium Digest*, Vol. 3 pp. 1713-1716, Phoenix Civic Center, Phoenix, AZ	**Conference Paper**
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6	2001	M. Urteaga, D. Scott, T. Mathew, S. Krishnan, Y. Wei, M. Rodwell "Single-stage G-band HBT Amplifier with 6.3 dB Gain at 175 GHz"	*2001 GaAs IC Symposium*, Baltimore, Maryland, October 21-24.	**Conference Paper**

7.	2001	M. Urteaga, D. Scott, T. Mathew, S. Krishnan, Y. Wei, M. Dahlstrom, M. Rodwell, "Characteristics of Submicron HBTs in the 140-220 GHz Band"	*2001 Device Research Conference*, Conference Digest, University of Notre Dame, Notre Dame, IN, June 25-27.	**Conference Paper**
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9	2001	M.J.W. Rodwell, Miguel Urteaga, D. Mensa, Q. Lee, J. Guthrie, Y. Betser, S.C. Martin, R.P. Smith, S. Jaganathan, T. Mathew, P. Krishnan, S. Long, R. Pullela, B. Agarwal, U. Bhattacharya, L. Samoska, Denis Scott, Mattias Dahlstrom, "Submicron Scaling of HBTs."	*IEEE Transactions on Electron Devices,* Vol. 48, No. 11, p. 2606-2624, November.	**Journal Paper (Invited)**
10	2002	M. Urteaga, D. Scott, S. Krishnan, Y. Wei, M. Dahlstrŏm, S. Lee, M.J.W. Rodwell, "Multi-stage G-band (140-220 GHz) InP HBT Amplifiers."	To be published GaAs IC Symposium, April 18.	**Conference Paper**
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